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HIGH POWER SPARK GAP SWITCH PROGRAM,(U)
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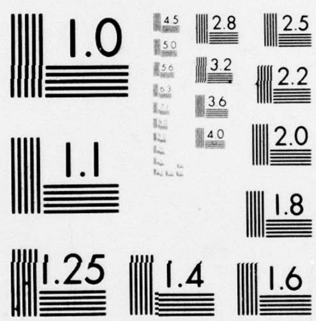

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A program is presently underway into the investigation and final development of a spark gap switch capable of operating at repetition rates of 50 to 250 pulses/sec (pps) at voltages of several hundred kilovolts and 5 megawatts average power. Results of an Aero Propulsion Laboratory program on High Power Spark Gap Switch Development led to the present study, which is a coordinated effort between the Gas Dynamics Laboratories of The University of Michigan, Naval Surface Weapons Center and Maxwell Laboratories, Inc. Theoretical investigations into the nature of dynamic nonstationary arcs under transverse gas

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20. ABSTRACT (Continued)

Flow conditions between electrodes are discussed. Future plans for experimental studies of arc properties include time resolved temperature measurements using a unique optical scanning system at The University of Michigan. An optimized high power spark gap switch will be designed and fabricated by Maxwell Laboratories and tested at their switch test facility.

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HIGH POWER SPARK GAP SWITCH PROGRAM

by

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ABSTRACT

We will highlight a program presently underway into the investigation and final development of a spark gap switch capable of operating at repetition rates of 50 to 250 pulses/sec (pps) at voltages of several hundred kilovolts and 5 megawatts average power. Results of an Aero Propulsion Laboratory program on High Power Spark Gap Switch Development will be given; it will be shown how these results have led to the present study.

The present investigation, a coordinated effort between the Gas Dynamics Laboratories of The University of Michigan, Naval Surface Weapons Center and Maxwell Laboratories, Inc., will be described. Theoretical investigations into the nature of dynamic nonstationary arcs under transverse gas flow conditions between electrodes will be discussed. Future plans for experimental studies of arc properties include time resolved temperature measurements using a unique optical scanning system at The University of Michigan. An optimized high power spark gap switch will be designed and fabricated by Maxwell Laboratories and tested at their switch test facility.

Introduction

In order to meet the needs for a triggered closing switch as part of high power conditioning networks, a high power spark gap switch investigation has been initiated. Present and future applications require closing switches beyond state of the art to connect pulse forming networks employing capacitive storage to respective loads. Candidates under consideration for operations at several MW average power consist of Thyratrons, Liquid Metal Plasma Valve (LMPV) closing switches and High Power Spark Gap switches. The latter will be addressed in this paper. Design goals of the past AFAPL (Air Force Aero Propulsion Laboratory) high power spark gap program as well as the present program are shown in Table I.

It would be difficult to try to describe all past efforts concerning High Power Spark Gaps. We singled out one program because of its importance and direct application to this present investigation. This investigation was based on the past results of the Air Force Aero Propulsion Laboratory Program(1).

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TABLE I. DESIGN GOALS (PER ELECTRODE PAIR)

	AFAPL Program	NSWC Program
Average Power	1.2 - 5.5 MW	2.5 - 5 MW
Hold-Off Voltage	20 - 100 KV	100 - 300 KV
Pulse Width	20 - 100 μsec	20 - 50 μsec
Energy per Pulse	2.4 - 55 kiloJoules	10 - 100 kiloJoules
Repetition Rate	100 - 500 pps	50 - 250 pps
Recovery Time	< 250 V/μsec	< 250 V/μsec
Lifetime	10^5 pulses	10^5 pulses
Efficiency	> 98%	> 98%
Weight, Volume	Minimum	Minimum

AFAPL Switch

The AFAPL switch developed by Maxwell Laboratories, Inc.,[1] for the Air Force is shown schematically in Figure 1. This spark gap switch or electrode pair consists of 2 inch diameter electrodes with overvoltage triggering. The electrodes are made of copper with elkonite (Tungsten-Silver) tips and are hollow. Dry air flows from inlets at rate of 150 cubic feet/minute (CFM) at each end of the switch and is exhausted through the hollow copper electrodes. The gap spacing (ℓ) of the electrodes was 0.5 cm.

The accomplishments per electrode pair for the AFAPL program are given in Table II.

TABLE II. AFAPL ACCOMPLISHMENTS (PER ELECTRODE PAIR*)

Average Power	1.4 MW
Hold-Off Voltage	20 KV
Pulse Width	≃ 20 μsec
Energy per Pulse	5.6 kiloJoules
Repetition Rate	100 - 500 pps
Gas Flow	150 CFM (Air)
Switch Grace Period	~ 700 μ sec
Charge Transfer per Pulse	280 mC
Lifetime	10^6
Efficiency	~ 99.7%
Weight	30 lbs
Volume	0.63 ft^3
Triggered	Overvolting Mode

*Two-inch OD electrodes made of copper and tungsten-silver tips.

The direction of the gas flow was found to be important since when the flow is in the opposite direction using the electrodes as the inlet and exhausting through the switch housing, switch recovery is observed to be much slower. This is probably due to the fact that this latter configuration results in a flow velocity which decreases in the direction in which the arc is being blown so that the hot gas slows significantly. When the gas is exhausted through the electrodes the flow increases toward the center of the electrodes so that the hot gas is pushed by high velocity flow out of the switch.

Present Investigations

The present program represents a coordinated effort involving a number of laboratories as illustrated in Figure 2. The Gas Dynamics Laboratories of The University of Michigan in conjunction with the Naval Surface Weapons Center has principally performed analytical studies into the nature of arc discharges formed by the operation of high power spark gap switches. A model of the spark gap switch operation has been formulated. Future plans call for experimental investigations of arc properties using a unique arc testing facility and optical scanning system at The University of Michigan.

An optimized high power spark gap switch will be designed and fabricated by Maxwell Laboratories and tested at their switch test facility[1]. Also to be used in this investigation are results of an AVCO High Power Spark Gap program at rep rates up to 20 pps. All these factors will be used to obtain an understanding of High Power Spark Gap switches at rep rates of several hundred pulses/sec and extend the present switching technology.

As a result of the previous study[1] under AFAPL and this program the following twelve variables were found to be important as regards to High Power Spark Gap operation. These variables are: Gap Spacing (ℓ), Electrode Material, Gas Pressure (P), Gas Type, Operating Voltage (V), Gas Flow Rate (Φ), Charge Transfer per Shot (Q), Grace Period (Tg), Current [i(t)], Recharging Risetime (Tr), Electrode Geometry, and Pulse Repetition Frequency (PRF in PPS).

However, many parameters are interrelated and dependent upon each other: gas flow in gaps is a function of electrode geometry, gas flow rate, gap spacing, gas pressure; breakdown safety factor is a function of gap spacing; max PRF is a function of recharging risetime; and grace period is a function of recharging risetime.

Restrike rate is a function of the risetime of the switch voltage with shorter risetime leading to higher restrike rates. Increasing the charge transfer per shot leads to increases in restrike rates, which also depends on repetition rate. As gas pressure (P) increases the spark gap breakdown safety factor (m) value increases but amount of gas flow necessary to remove the additional gas increases. Increasing the gas velocity decreases the restrike rate in spite of fact m value is decreasing. In rep pulse mode increasing the inter-electrode gap spacing (ℓ) leads to an increased restrike rate. Increasing the gap length (ℓ) decreases the gas velocity between electrodes.

For high power, rep rate spark gap switches it was determined that the gas flow in gaps was the most important parameter both for cooling and restoring the dielectric strength of the gas. It was found that smaller diameter electrodes (all other parameters fixed) operated much better at higher voltages and required lower flow rates than larger diameter electrodes.

In order to operate at voltages of 200 to 300 kV, a spark gap must either operate at rather high gas pressure or long gap lengths or a combination of both. Assuming the gas is dry air with a hold off voltage of ~ 25 kV/cm per atmosphere, more than 5 atmospheres of pressure are required for a gap spacing of 2 cm. Both the high gas pressure and

the long gap spacing lead to high gas flow requirements. At five atmospheres, five times as much volume gas flow is necessary as would be required at one atmosphere. On the other hand, increasing the gap length necessitates increased volume gas flow in order to maintain a constant flow velocity in the gap region. As a result of these considerations, it can be seen that the design of a gas flow spark gap to be operated at high repetition frequencies and high voltage involves a careful balancing and optimization of several factors.

Analytical Studies

During normal operation of a rep rate spark gap switch energy is deposited in the spark channel by joule heating during the conduction cycle. This energy is partly radiated away, partly conducted to the electrodes, and partly removed by convection, molecular and turbulent diffusion, and shock waves. The important energy loss mechanisms are radiation and convection. For the switch to function properly, it is necessary that the dielectric strength of the gas be restored after each shot before voltage is reapplied. Otherwise, the switch will restrike prior to the next pulse. In order for the dielectric strength of the gas to be restored between shots, it is necessary to remove or cool the hot gas generated by the spark. The electrodes themselves are also cooled by the gas flow. Gas flow cooling is especially important for high power repetitious spark gaps.

A numerical model has been developed to observe the effects of variable switch geometry and gas flow rates, on the dielectric recovery time. Arc temperature, radius, and length are calculated as functions of time, as well as the magnitude of the heat transfer mechanisms and flow velocity.

The spark gap switch is modelled by two electrodes, with geometry as shown in Figure 1. The transverse flow complicates the analytical model in that boundary conditions commonly used for wall stabilized arcs are not applicable. Instead, the partial differential equations governing heat transfer will be simplified by assuming a uniform radial temperature profile. The governing equations become:

$$\rho C_p \frac{dT}{dt} = \frac{I^2}{\sigma A^2} - \varepsilon U - 4\pi \frac{kT}{A} \tag{1}$$

$$\frac{d}{dt}(\rho C_p TA\ell) = \frac{I^2}{\sigma A}\ell - U A\ell - Nu\, kT\pi\ell \tag{2}$$

$$Nu = .466\, Re^{.615} \tag{3}$$

Equation (1) is the energy balance on the arc centerline. The arc centerline temperature T and area A are to be determined as functions of time t. The radial conduction losses in the partial differential equation have been approximated by $-4\pi kT/A$ which would be exact for the case of a parabolic temperature profile. Total radiation losses U(T) in watts/cm^3 for high temperature air at one atmosphere have been calculated by Hermann and Shade[2]; ε is a factor greater than unity that includes reabsorbed radiation and is determined from the same reference. Density, ρ, heat capacity, C_p, thermal conductivity, k, and electrical conductivity, σ, vary with temperature according to calculations of Yos[3] for air.

Equation (2) is the boundary condition that defines the arc area such that total energy balance is satisfied, similar to that of Frost and Liebermann[4]. Forced convection losses from a cylinder in transverse flow are given by Equation (3) for Nusselt number, Nu. Reynolds number, Re, is the relative velocity, U_r, times arc diameter divided by free stream kinematic viscosity. Photographs of Mallairis[5] show the relative velocity to increase in time; the arc initially moves at the gas velocity while U_r peaks when the arc finally remains fixed at the inner edge of the electrodes.

The variation of arc length, (ℓ), is important in the final cooling process and is determined from:

$$\frac{d\ell}{dt} = \frac{2\dot{V}}{\pi} \frac{\sqrt{d^2 - (\ell - h)^2}}{[D - \sqrt{d^2 - (\ell - h)^2}](h - \ell)\ell} \tag{4}$$

where $\dot{V}$ is the gas flow rate in CFM, h is the separation of toroid axes, and D and d are the major and minor diameters of the toroids.

The simplifying assumption of a rectangular temperature profile was applied to a steady state arc by Lowke[6]; he found good agreement with experiment. Previous work[7] has shown optically thin radiatively cooled arcs to be isothermal. The model developed with the isothermal approximation is especially attractive since all the important heat transfer mechanisms can be included, and changes in their magnitudes can be easily explained.

Solutions to Equations (1)-(4) were obtained using Hamming's modified predictor-corrector scheme. The scheme is a stable fourth order integration procedure initiated by a Runge-Kutta technique; the correct step size is determined for maximum accuracy.

Experimental data and dimensions of the AFAPL spark gap switch[1] as shown in Figure 1 were used. The minimum gap spacing was 0.5 cm and peak currents were 2.3 and 15 Ka in two series of tests.

Results for one typical spark gap firing are shown in Figure 3. Joule heating causes rapid increases in arc temperature and diameter. Radiation losses are dominant immediately after the current pulse, until the arc temperature decreases below 10,000°K. Convective cooling and arc stretching then dominate as the hot gas continues to move downstream with the flow. When the arc reaches the inner edge of the electrodes, the large relative velocity causes rapid convective cooling.

The results obtained are now being used to predict the dielectric recovery of the gap. Design tradeoffs are being studied to minimize gas flow rates yet also minimize dielectric recovery times.

Experimental Studies of Arc Properties

In order to simulate the spark gap operations, The University of Michigan Cascade Arc Facility[8] will be used for future experimental measurements of arc properties. Experimental measurements of arc temperature, diameter and relative velocity are important as inputs to the model under development. A schematic of this facility is shown in Figure 4.

Repeatable and controlled arc conditions will be studied using advanced diagnostic techniques. Pulsed arcs can be generated in subsonic and supersonic air flows using a capacitor bank network for current pulses of many kiloamperes. A computer controlled spectrographic system is presently used to measure radial temperature profiles in time varying arcs. Photographs of the arc are being made at 2×10^6 frames/sec.

Summary

We have briefly described a program aimed at understanding and developing high power spark gap switches for high rep rate and high operating voltage conditions. The program has only recently been initiated. Further experimental and analytical investigations of arc-air flow interaction will be made to extend and determine limits of spark gap technology, if any.

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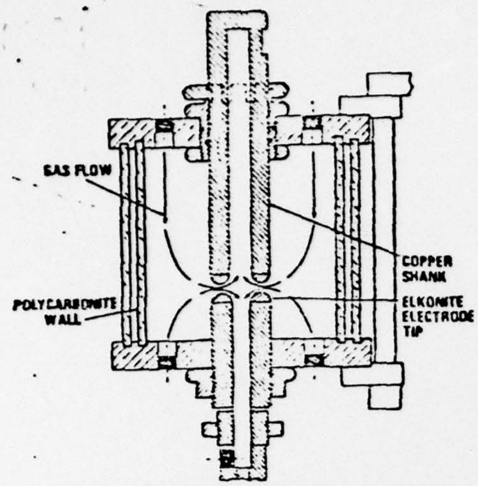

FIGURE 1. SCHEMATIC OF HIGH POWER, HIGH REP RATE SPARK GAP SWITCH (2 INCH DIAMETER ELECTRODES)

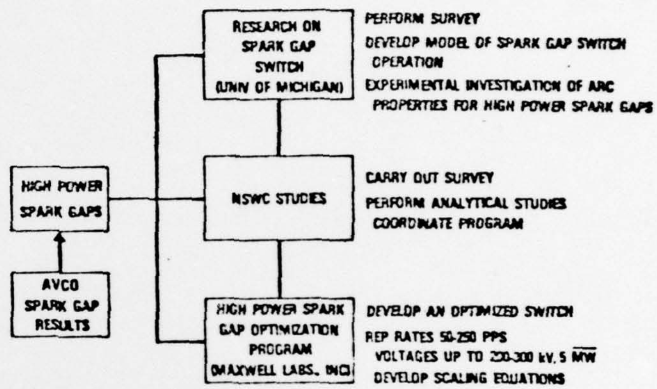

FIGURE 2. PROGRAM OUTLINE

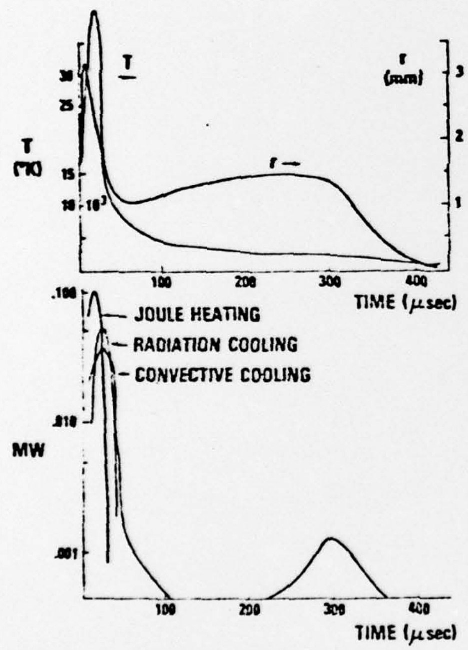

FIGURE 3. CALCULATED TEMPERATURE, RADIUS AND HEAT TRANSFER TERMS FOR AFAPL SPARK GAP SWITCH

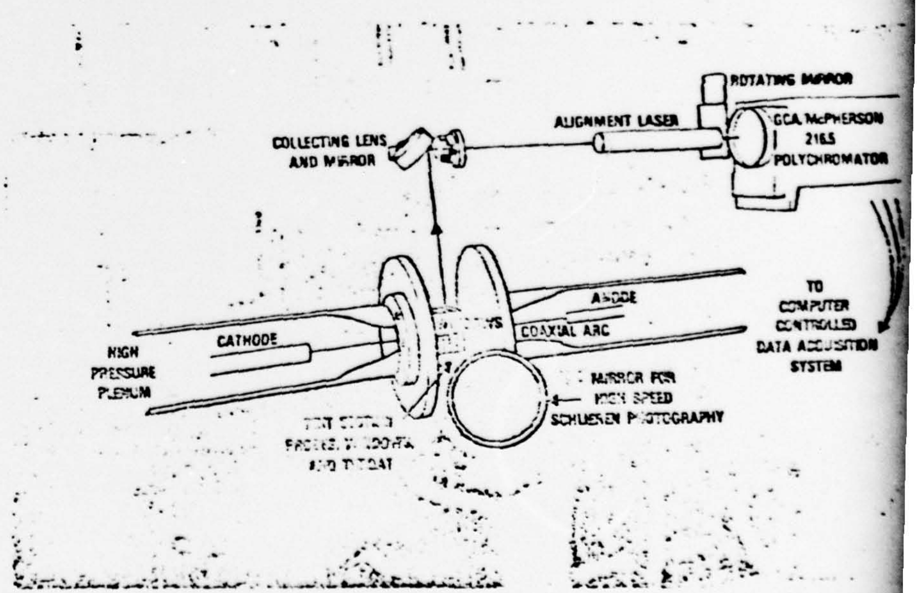

FIGURE 4. UNIVERSITY OF MICHIGAN ARC FACILITY, GAS DYNAMIC LABORATORY WITH COMPUTER CONTROLLED POLYCHROMATOR AND SCHLIEREN SYSTEMS